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An Integrated Vision Touch-Probe System for Inspection Tasks

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A coordinate measuring machine (CMM) is a highly accurate three-degree-of-freedom Cartesian robot often used for dimensional inspection of mechanical manufactured parts. Dimensional inspection involves measuring the relative geometry of surface features and determining whether they are within tolerance. Examples of geometries evaluated by such a system include smooth surfaces, distances between edges, positions of holes, and diameters and shapes of holes.

Applications in the automobile or aircraft industries require measurement accuracies on the order of 25 micrometers. Virtually all CMMs in use today use touch-trigger probes. While extremely accurate, the data acquisition rate of touch-trigger probes is very slow, about one point per second. This type of probe is not suited for gathering dense surface data—important for parts with complex geometries—or locating part edges that contain important measurement information.

Experiments were done to increase the speed and flexibility of CMM data acquisition while maintaining accuracy, and to simplify measuring geometrically complex parts. The test procedure investigated the interaction of a video camera and an analog touch probe within a hierarchical control system to control probe motion.

> Real-time vision can guide the probe to features of interest where probe measurements provide necessary inspection data.

Vision Touch-Probe Equipment

The equipment used in the investigation includes a three-degree-of-freedom CMM as described, multiple interchangeable probes, a black-and-white CCD camera with a 16-mm lens, framegrabber, Sun SPARC5 workstations, and VME-based multiprocessor system running a vxWorks operating system. Code is written in C++ on the workstations and downloaded to the vxWorks system. The purpose of the experiment described here is to demonstrate our real-time control system in which computer vision is used to determine the distance from the probe to a goal edge as the probe scans over a planar surface. This distance is used to control the speed of the probe as it nears the edge. Although the testbed is equipped with many probes, this experiment uses only one touch probe.

The low resolution of the camera prohibits the use of visual data for precise part measurements. However, vision can provide position estimates of features of interest on the part. Real-time vision can guide the probe to features of interest where probe measurements provide necessary inspection data.

Probe motion is controlled by using feedback from the vision system as it tracks the moving probe. This lets parts be measured even if an accurate inspection model is unavailable. In some cases, such control eliminates the time-consuming step of part setup, which uses

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fixturing or other methods to register the test part with the model.

Information from three sensors—the camera, the machine linear scales, and the probe itself—control the motion of the probe as it scans across a surface. Vision picks up information on part features such as edges, holes, and grooves, while machine scales—when used in conjunction with vision—provide distance of the probe from these features. The probe data provide the displacement of the probe from the part surface. By fusing all forms of information, the control can scan part surfaces quickly, using visually detected edge proximity as feedback to control CMM arm motion.

Vision & Touch Sensors

A camera is a noncontact sensor with a high data-acquisition rate. Visual data may be characterized as being of a global nature, meaning it provides the user with an overall view of a scene or application. Although camera data are generally noisy, an image containing between 65,000 and 262,000 pixels can be read in 16 milliseconds. Image processing algorithms can then locate and measure global features of interest in the scene such as object edges, corners, and centroids.

The problems associated with using camera data can be divided into two classes: geometric constraint and radiometric constraint problems. Geometric constraints include visibility, field-of-view, depth of field, and pixel resolution. The radiometric constraints include illumination, specularity, dynamic range of the sensor, and contrast. Currently, this work is not using an active vision system that can overcome some geometric and radiometric constraint problems.

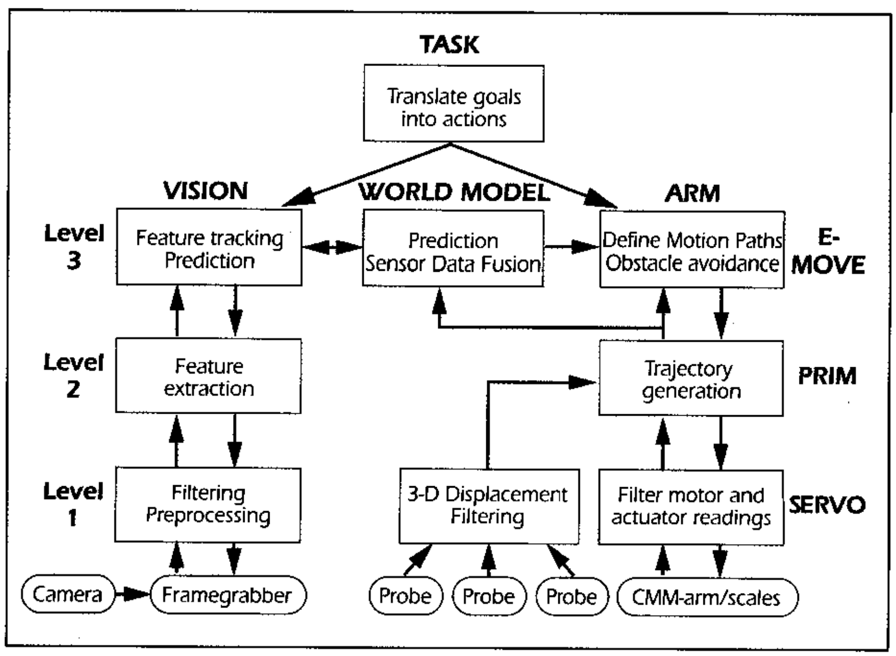
Touch trigger probes used in most CMM applications are contact sensors. These are highly accurate with very little noise associated with their data. However, the data they extract are of a local nature, applying only to the specific points touched. Since information is read one point at a time, the touch probe is unsuitable for rapid high-density data acquisition. Touch probe systems are also crash prone if the part being inspected is not fixtured exactly in accordance with the CMM program.

Single-sensor systems are limited in their ability to sense and identify meaningful features under varying conditions. Multiple sensors can overcome the problems possible with a single sensory input, but create problems concerning the interpretation and possible merging, or fusion, of multiple sensory outputs. To take advantage of the strengths of both the camera and touch sensor and to overcome their individual shortcomings, the experimental system was designed as an integrated vision touch-probe system. The system has the ability to gather high-bandwidth global information and to obtain highly accurate measurement information.

The Integrated System Architecture

The parts-inspection test-bed incorporates a hierarchy of controller nodes, each with an assigned set of responsibilities that include sensory processing (SP), world modeling (WM), and behavior generation (BG). *Figure 1* shows the functional architecture of the integrated system. Each rectangle represents a controller node in either the sensory processing hierarchy or the controller hierarchy at a specific level. Each node consists of SP, WM, and BG modules that may communicate with one another.

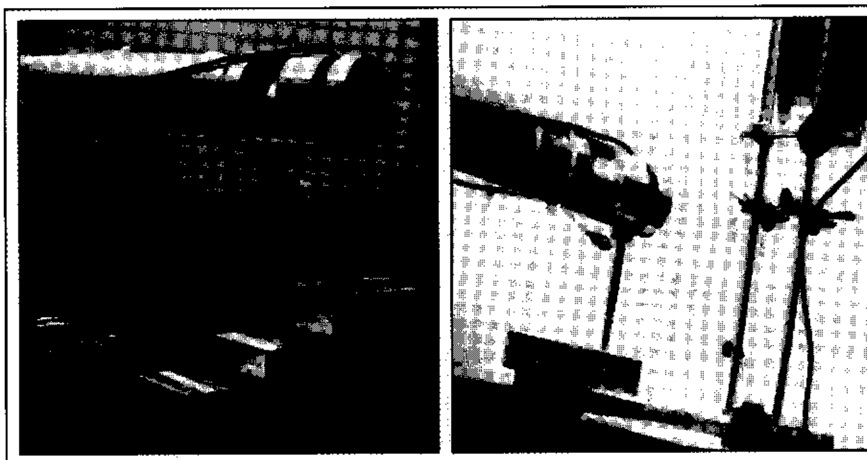
The Servo level is the lowest level of CMM arm control. It translates programmed positions into commands of the motors' actuators. The next level, Primitive or Prim, computes inertial dynamics and generates smooth trajectories. Its output to the Servo level consists of evenly spaced trajectory points. The third level, Elemental or E-move, transforms symbolic commands for elemental movements into strings of intermediate position that define motion



1. Schematic of the NGIS control system architecture.

pathways free of collisions and kinematic irregularities. The fourth and highest level, Task, transforms goals defined in terms of desired actions to be done on objects into a series of E-moves designed to achieve these actions.

The role of the sensory processing system is to extract information about objects, events, and relationships in the world to keep the world model accurate and up to date. World-model processing modules generate predictions of expected sensory input during inspection and make predictions based on the fused-sensory information. The model also maintains a knowledge database that keeps its internal representation current and consistent with the external world.



2. The NGIS testbed: on the left, the probe attached to the CMM arm measures the surface of a rectangular step part; on the right, the probe is shown in relationship to the camera mounted on the CMM table.

Sensory processing is hierarchical with the lowest level gathering raw information from each sensor and filtering the information. In a vision system, the sensor is one or more cameras.

Level 1 vision processing reads an image frame digitized from the camera and filters the image to enhance its quality. Image processing at this level is limited to point features. The analog touch-probe reads accurate probe displacement values within its own coordinate system. These readings are filtered before being made available to the arm control.

Level 2 analyzes the image output from Level 1 to detect 2-D image features such as edges, corners, and regional attributes such as areas, perimeters, centroids, and cavities. If sufficient information exists, the 2-D features transform into a 3-D coordinate space. This transformation expresses features in a coordinate system common to that of other positional sensors.

The third level of the vision processing system tracks features on moving objects and detects possible collisions. The arm hierarchy integrates filtered displacement values computed by the probe system with filtered arm scale readings. This integration uses calibration constants obtained off-line for the machine and probe and locates the probe tip in the machine coordinate system.

An Integrated Vision Touch-Probe System

The camera mounted on the CMM surface remains stationary relative to the part on the table. In *Figure 2*, the left image shows the probe attached to the CMM arm measuring the surface of a rectangular step part. The right image shows the relationship of the camera mounted on the CMM table to the probe. The camera output is captured by a framegrabber that digitizes it to a 512 × 512 resolution. The CMM table moves in the Z direction, and the arm moves the probe along the *XY* axes. To position the probe, the controller positions the CMM table and the probe in a coordinate system relative to a predefined origin.

Lighting conditions and specularity can create image processing problems when parts being measured are machine finished to a high gloss. The glare and reflections from overhead lighting introduce shadows and artifacts that interfere with image-processing algorithms. This test system polarized the overhead lighting to reduce specularity. This relatively simple and inexpensive technique uses sheets of polarizing filters attached to the fluorescent light fixtures in the laboratory. In addition, a rotating polarizing filter attached to the camera lens adjusts to select light polarized at 90° from the overhead filters. Polarizing filters do not eliminate the problems of specularity, but greatly reduce these effects.

Processing Vision Data

The global information generated from the vision system guides the movement of the touch probe across the surface of the part. Vision provides information about positions of part features and identifies the probe, tracking its position as it inspects the part. The probe data provide displacement from the part surface, and, in conjunction with the machine scales, the probe position. Using a fused representation of this information, the controller can scan the probe quickly over smooth surfaces, stopping at part edges.

Visually derived feedback for the system consists of the distance in terms of pixels between the current position of the probe and the goal edge. The vision system performs the following processing steps to provide this information:

- Segmentation of the part surface to be scanned from the total scene.
- Extraction of pixels representing edge or perimeter points.
- Fitting edge pixels to lines or curves.
- Defining initial probe position in image coordinates.
- Tracking probe as it moves along the part's surface.

Segmentation

The first step in vision processing requires that the part being inspected be separated or segmented from other things in the field of view. Segmentation algorithms are scene, or application, dependent: there is no single segmentation algorithm that is always successful. This experiment segments a step block from the workplace scene by using a simple thresholding algorithm. Thresholding involves comparing each pixel in the image to some number t. If the pixel value is greater than t, the threshold value is white; if it is less than t, the value is black. When t is chosen appropriately, the part and background are clearly separated.

A connected component algorithm was used in this investigation to segment a piston from its background. This algorithm processes a binary representation of the original scene and uniquely labels all connected regions. Knowledge about the part lets us identify the region that represents the part surface.

Extraction of Edge Pixels

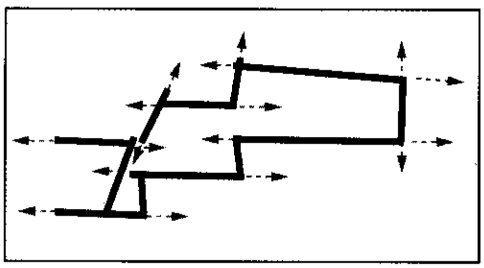
There are a number of edge-detection algorithms that can extract pixels that represent edges. An edge is defined as the transition between a dark and a light region, or conversely, a light and dark region. When a part is cleanly segmented from any background information, an edge-detection algorithm can easily label all points representing its boundary points.

When using the connected component algorithm for segmentation, a boundary tracing algorithm extracts the edge pixels representing the boundary points on the region of interest.

Line or Curve Fitting

A Hough transform was used to fit the extracted edge points of the step block into straight lines. *Figure 3*, showing representative results for the step-block, displays a graph of the extracted edge points overlaid with the lines selected by the Hough transform.

To fit the edge pixels extracted from the circular piston to a curve, a least-squares-fitting algorithm was used. Because of image distortion, the projected image of the piston appears to be elliptical in shape; therefore, the points are fit to an ellipse.



3. Extracted edge pixels and fitted lines (dotted lines).

Initial Probe Position

To determine the initial position of the probe, it is assumed the controller always places the probe in a pre-defined 3-D position on the part's surface. Using an off-line operation, the system operator determines the probe's approximate location in image coordinates by examining the image. The operator's coarse estimate in image coordinates defines a small window in the image representing the tip of the probe. The window defines a 10 × 10 gray scale template used in a correlation tracking algorithm.

Initial experiments assumed the probe's motion while scanning along the surface is a straight line path. We compute a vector in the image plane in the direction of motion. This calculation is from the initial probe position and a second image position computed as the probe moves or from operator input. The intersection in the image plane of the motion vector and the nearest part edge represents an initial estimate of the probe's 2-D goal point. The distance between the initial position and the goal position is measured in pixels.

Tracking

As the arm moves toward its goal position the probe is tracked using the predicted probe-image velocity and a correlation algorithm for the sum of absolute differences (SAD). A predictive filter determines probe position and velocity at the next time interval. The prediction is based on a weighted sum of the current position and velocity, and a history of past positions and velocities. Varying the weights can tune predications to be more responsive to new readings or to respond smoothly over time.

At each processing iteration, the search direction and window used for the SAD correlation are re-computed based on the predicted probe image position and velocity. The size of the search window is determined by the probe velocity magnitude. The direction of search is biased in the direction of velocity.

The probe position is computed to be the position that yields a minimum value for the sum of absolute differences over the search space. The correlation template is updated each cycle to reflect the current gray-scale information representing the

ACTING LEVEL	COMMANDED ACTION
Arm E-move	Move arm near part.
Vision Level 3	Extract and define edges of part in field-of-view.
Arm E-move	Place probe at predefined starting position on part surface.
Vision Level 3	Extract 2-D position of probe on part surface.
Vision Level 3	Determine 2-D goal point of expected probe trajectory.
World Model	Fuse image coordinate data with 3-D data. Predict distance in mm between probe and part edge.
Arm E-move	Scan surface until proximity to goal is less than threshold.
Vision Level 3	Loop and track probe; report distance to edge.
Arm E-move 3	Terminate tracking.

4. Table showing the demonstration scenario, with controller task levels and the commanded actions.

probe position.

Visual feedback to the system consists of updates of the 2-D distance between the probe and the nearest edge. The current position and the intersection point on the edge update each processing cycle. The world model fuses the visual information with the 3-D position and velocity information supplied by the CMM, and predicts the 3-D distance remaining between the probe and the part's edge.

Vision Touch-Probe Operation

The experiment is initiated by the controller task level, referred to as Task in *Figure 1.* Commands are sent to the Elemental level (E-move) and to the Vision Level 3 process via a common-memory interface. *Figure 4* describes the commands generated by Task that are sent to either Arm E-move or Vision Level 3 processes. The command to extract and define edges of the part in the field-of-view occurs just once for a particular field-of-view. This means the edge extraction and line or curve fitting processes, which are time consuming, run only once. The probe tracking process, however, is updated every processing cycle. Both the arm control and vision processes decompose their commands for the levels below them. Status information sent to the appropriate process indicate either completion of the command or an error condition. Visual tracking is terminated when the closest edge is detected as being less than a pre-defined δ millimeters away from the current probe position.

Visual processing is done on the multiprocessor system using only the framegrabber, resulting in long processing times for the computationally intensive operations such as convolutions, line or curve fitting, and SAD correlation algorithms. The time-critical components for real-time visual processing are data acquisition and the SAD tracking algorithm. The system only does edge extraction and line fitting during initialization of the run.

The time to do a tracking iteration is approximately 100 milliseconds. Since the predictive filtering in both the vision process and world-model process requires uniform timing intervals, the maximum iteration time of 100 milliseconds is imposed on the vision process. This time is decomposed as shown in *Figure 5.* Tracking-related computations should reduce with systems having faster microprocessor boards.

Our ultimate goal is to develop scanning-control algorithms operated by sensor servos that can be transferred to manufacturing plants. The initial experiments involve a single scan of the part in along the X axis within the CMM coordinate system. Future work will investigate a continuous raster scan of a part using visual feedback to detect part boundaries. Including additional image processing capabilities to the vision-touch probe system should provide detection of features such as curved edges, holes, and grooves on complex parts.

Investigations are currently underway for fast, easy-to-perform calibration methods to register image space with CMM space. Such methods will let operators visually servo the arm to features of interest and to inspect and follow linear and curved contours. ■

TYPE OF PROCESSING	TIME (in 10-millisecond units)
Digitize and store image frame.	a=~6
SAD correlation.	b=~2
Filter and predict next probe location.	c=~1
Time delay.	10-(a+b+c)

5. Image processing timing.

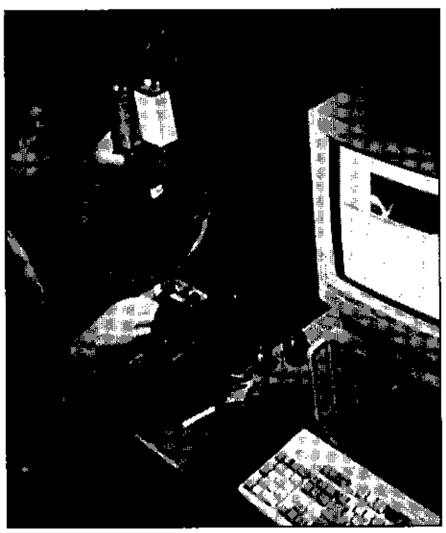
New Vision Systems for Inspection

With Arachne, a portable web inspection system from Datacube Web Systems (Danvers, MA), web integrators can evaluate samples in their laboratories—or at the customer site—to determine specific requirements for a full-scale web inspection system. The fully functional pilot-scale system evaluates defects under real conditions—analyzing effects of ambient lighting, temperature, dust, moisture, and vibration—to give a more accurate indication of the requirements of an inspection system. It also takes into account variation in machine speed, lens effects, and defect contrast, size, density, and orientation. Operators see continuous, real-time video images of the web showing all its characteristics, including defects, that are present at that point in the operation.

Web materials include paper, film, and textiles, 10 m wide and traveling at 1500 m/min. Arachne detects defects as small as 25 microns, with these features: Web Real-Time Disk for capture and playback of images to build a defect image database and evaluate image processing techniques; analysis software for quick, easy evaluation of computer algorithms and image processing solutions without programming; and Black Widow Web Inspection Engine for implementation of the image processing solutions on captured defect images or on the product on-line. Call (508) 777-4200.

Flexbar Machine Corp. (Islandia, NY) added the Opti-Flex Granite Z System to the product line of its new video inspection and measurement division. Granite Z Basic Measurement System is a complete turnkey measurement and inspection system with a solid Metrology Grade column and base for stability, and a large 8 × 4" precision crossroller positioning stage that may be supplied in a manual or motorized format. Video zoom optics provide a clear, crisp image with a standard magnification range of 17× to 108×, upgradeable to more than 1000×. The image is prominently displayed with a digital crosshair in full color S-Video format on a high-resolution Sony Trinitron Monitor. Call (800) 879-7575.

Rockwell Automation/Allen-Bradley (Bloomington, MN) introduced CVIM2 TurboTrack for in-



specting multiple independent lines or multiple stations on one line. Features include configuration of up to 32 gages or 32 windows in the same tool; remote I/O discrete bit messages, which write directly to the controller's remote I/O input table without using block transfers; unsolicited block transfer reads; tool groups for pass/fail outputs that consolidate pass/fail/execute status; overlap of up to 20 images for high burst inspection rates; and part tracking, which lets the system delay availability of pass/fail inspection results until the parts reach the point at which the appropriate accept/reject action can be done. The flexible, industrially hardened device works in demanding applications such as packaging, pharmaceutical and medical parts, discrete parts, consumer products, and electronics and semiconductor fabrication. Call (800) 223-5354.

The 5D Dynascope and 5E Dynascope by Vision Engineering (New Milford, CT) do optical inspection and dimensional measurement for macro and micro applications, respectively. They both offer accuracy and repeatability, as well as high-resolution, true binocular images with sharp depth of field for eliminating operator eye strain or fatigue. The 5D is equipped with QuadraChek 4000 measurement software that lets users visualize the work as they measure, while improving part throughput and automating inspection. The 5E provides magnification of 25× to 1000×.

Also from Vision Engineering, the Workshop Dynascope offers the benefits of an optical comparator, with versatile noncontact measurement and a fatigue-free projected image, but also offers an optical image like a traditional microscope, resulting in distortion-free resolution suitable for general inspection. Tasks such as measuring axes, diameters, and angles, as well as inspecting for flash, burrs, gouges, and machine tool chatter, are done on one instrument, saving time and money. Call Vision Engineering at (860) 355-3776.

Imaging Technology's (Bedford, MA) Intelec Products Div. provides the Prophecy 500™ (photo), a machine vision system based on a standard Microsoft Windows™/ Intel Pent-ium™ PCI bus platform, improving performance and ensuring a broad industry support for future system expansion. It does complex vision tasks for industries such as automotive, electronics, textile, food processing, pharmaceutical, packaging, metal forming, and aerospace manufacturing. The company's SherlockPro™ software uses a set of menu-based tools and options to build, modify, customize, and execute the complete machine vision application from image acquisition to control of I/O for process results. It provides a graphical environment for setting up inspection, tolerance, and input/output operations. Call (617) 275-2700 or (800) 333-3035.

Any combination of measuring, gaging, position, and detection inspections can be done at high speed by Checker 1, an automated industrial vision system from Image Modules (Epsom, Surrey, England). Optics, sensor, processor, and software are integrated into one compact, easy-to-install package. Ten separate line checks are available for gaging widths, measuring positions, calculating angles, finding centers, counting features and detecting parts. Ten area checks are also available for calculating areas, quantifying brightness, measuring size, assessing coverage, finding centers and evaluating textures. Inspections for 16 different products can be stored in the system, which handles more than 3000 parts per minute. Checker 1 mounts directly to the production line or on an optional bracket that provides five-axis adjustment. Call 011-44-1372-726150.

For remote visual inspection, Olympus America Inc. (Melville, NY) Industrial Products Group introduced two portable units that combine a built-in light source and video imaging equipment for video imagescopes, flexible fiberscopes, or rigid borescopes. The ILK-C Video/ Light Source Combination Unit comes with a 150-watt halogen lamp, IV-5A CCU, and monitor—or with a camera/storage compartment instead of the IV-5A, to accommodate another type of video camera. The other combination unit, the MH-542 Video Frame, accepts a 300-watt ILV-2 light source as well as the IV-5A CCU or a camera/storage compartment. The IV-5A's features include an integration circuit that increases light sensitivity for imaging in low light levels, high resolution, digital freeze-frame, and automatic light source brightness, gain control, and white balance. Call (516) 844-5888.

Qtec Industrie-Automation GmbH (Munich, Germany) is offering several inspection systems for various applications. The compact Mark camera and illumination inspection system combines selectivity with a low pseudo-reject rate due to combined algorithm from artificial intelligence and statistical correlation. Ink or laser marks are possible, with no limit on number of lines/characters. Individual characters or areas may be excluded from checking, and tolerances may be specified individually per character. It integrates into existing handling systems and may be combined with the 3-D lead measurement system.

The 3-D lead measurement system offers high precision with its combination of optical elements and subpixeling software as well as a true three-point seating plane algorithm. One camera, together with an optically tooled inspection site, is used for a full 3-D image, resulting in compact setup easily integrated into existing machinery. The calibration process is entirely automatic, and a calibration block is provided. Statistical summaries may be displayed or printed, or a complete SPC analysis may be carried out by an attached host computer.

Qtec also offers systems for radial component geometry measurement and stamped products geometry measurement. The former system does high-precision lead and body measurement with a compact unit made up of one camera and light source. Any two-lead or three-lead component (LEDs, transistors, ICs, capacitors, etc.) may be inspected; other options may be provided.

The latter system brings the accuracy of laboratory equipment to the stamping process, providing all functions necessary to configure a measurement scheme for any product that may run on the target machine. Two cameras can be attached simultaneously to allow for different views on the product. The measurement system offers interfaces to the machine control unit to allow for synchronization and monitoring the system's operation. Measured data can be exported on-line to external agents for statistical process control.

For more information on these products, call (089) 613 75 9-0.

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Robotics, Motion, and Machine Vision in the Automotive Industries
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LASER '97: 13th International Trade Fair and International Congress
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Max Planck Institute for Quantum Optics, Messe München
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